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Muon physics programs at J-PARC

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Abstract

The Japan Proton Acceleration Research Complex (J-PARC) has started supplying proton beams for various applications, including particle physics experiments. These particle physics experiments use secondary beams produced from the intense primary proton beam with a pulsed time structure provided by J-PARC. In this presentation, we will describe the current status and future plans of the J-PARC project with particular focus on particle physics experiments using muons.

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*Keywords:*muon; mu-e conversion; g-2

1. Introduction

The Japan Proton Acceleration Research Complex (J-PARC), a joint project between KEK and JAEA, is a new accelerator research facility that produces megawatt-class proton beams at both 3 and 30 GeV [1] and also provides various types of secondary beams produced by proton–nucleus reactions, such as neutrons, kaons, pions, muons, and neutrinos. The three major scientific goals of the project are to support studies on particle and nuclear physics, studies on materials and life science, and R&D on nuclear transformation. Work on the first two began after the accelerator successfully started supplying the proton beam in 2008, and the last goal is considered as a major subject in the second phase of the project.

The accelerator complex is composed of a chain of three accelerators: linear accelerator (LI), rapid-cycle synchrotron booster (RCS), and main ring (MR). Protons (H^-) produced at an ion source are accelerated to 141 MeV in the LI and then injected into the RCS after stripping the electrons using a graphite stripper foil. In the RCS, the protons are accelerated to 3 GeV and extracted for further acceleration in the MR or are used to produce muon and neutron beams for materials and life science programs. Protons transferred to the MR are further accelerated to 30 GeV and extracted for use in particle and nuclear physics experiments. There are two extraction modes in the MR, called the fast- and slow-extraction modes. The former supplies a proton beam without destroying its bunch structure and is mainly used for neutrino production. The neutrino beam thus produced is directed toward the super-KAMIOKANDE detector located 295 km away from J-PARC for the neutrino oscillation experiment (T2K) [2]. The

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latter is used to supply a continuous proton beam to the experimental hall. This is realized by destroying the bunch structure after acceleration and by applying active feedback to the beam orbit to flatten the time structure of the extracted beam. This beam is used to produce secondary beams such as kaons, pions, and muons for use in particle and nuclear physics experiments. At J-PARC, two experimental halls are available: one is the Materials and Life Science Experimental Facility (MLF) and the other is the Nuclear and Particle Physics Experimental Facility (NPF). Several particle physics programs are in progress at these experimental facilities, such as the neutral kaon rare decay, $K^0 \to \pi^0 \upsilon \bar{\upsilon}$, search experiment (KOTO) [3] and T-violating muon transverse momentum measurement in $K^+ \to \pi^0 \mu^+ \upsilon_\mu$ decays (TREK) [4].

Figure 1 shows the upgrade schedule for the accelerator power. Currently, the J-PARC accelerator is operated at 100 kW for fast extraction and 3 kW for slow extraction. However, meticulous studies are in progress to increase the beam power in a step-by-step manner without increasing beam loss, which might cause radioactive contamination in the accelerator equipment. It will take approximately five years to reach the design beam power. For this, it is necessary to upgrade the LI acceleration energy from 141 to 400 MeV. The installation of new acceleration cavities in LI will be completed during the summer shutdown in 2013.

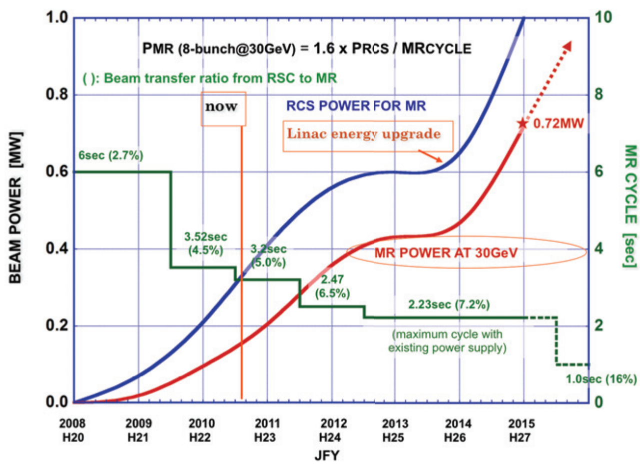

Figure 1: J-PARC accelerator power upgrade plan shown in Japanese Fiscal Year (JFY). JFY starts in April and ends in March in the next calendar year

2. Muon programs at J-PARC

The particle physics experiments using muons constitute the principal project at J-PARC. Thanks to the high accelerator power and suitable time structure of accelerations, intense pulsed muon beams are available at both the MLF and NPF. Currently, three major particle physics experiments using muons are planned: two mu-e conversion search experiments and one experiment to measure the muon anomalous magnetic dipole moment (g-2) and electric dipole moment (EDM). These experiments are expected to play an important role in exploring new physics beyond the standard model. It is considered that new experiments with better sensitivity than ever achieved so far should be carried out in parallel to those exploring high-energy frontiers, such as the LHC experiments.

2.1. Mu-e conversion search experiments

The standard model of particle physics successfully describes the behavior of known particles, although its incompleteness has been pointed out for many years. New physics models introduce new partners for the standard-model particles to resolve this incompleteness. The supersymmetric extension of the standard model is one such new model that predicts an observable rate for the mu-e conversion process just below the current experimental bound of

7.6×10^{-13} [5]. Because the charged lepton flavor violation process such as the mu-e conversion is strictly forbidden in the standard model or is negligible even if we take into account neutrino oscillations, experimental observation of the mu-e conversion process will be strong evidence of new physics beyond the standard model.

At J-PARC, two mu-e conversion search experiments are planned to reveal or restrict the new physics: The Coherent Muon to Electron Transition (COMET) experiment will search for the mu-e conversion process with almost 10,000 times better sensitivity than the current experimental bound [6,7], and the Direct Emission of Electrons by Muon-Electron Conversion (DeeMe) experiment aims to improve upon the current experimental bound (or discover phenomena if possible) with less sensitivity than COMET but with a shorter preparation period and lower construction cost [8].

The COMET experiment aims at a sensitivity of 10^{-16} for the mu-e conversion process using the pulsed muon beam provided at NPF. When a muon (μ^-) is stopped in a material, it is trapped by a nucleus to form a muonic atom. The muon in a muonic atom usually decays into an electron and two neutrinos ($\mu^- \to e^- \nu_\mu \overline{\nu_e}$), called muon decay in orbit, or is captured by the nucleus followed by a neutrino emission ($\mu^- + (A,Z) \to \upsilon_\mu + (A, Z-1)$), called muon capture. The muon in a muonic atom decays via either process with a lifetime in the order of 1 μs, depending on the nucleus (0.88 μs for aluminum). The lepton flavor is conserved in these decay modes. However, when the mu-e conversion occurs ($\mu^- + (A,Z) \to e^- + (A,Z)$), the lepton flavor numbers at the initial and final states are different because there is no neutrino emission in the final state, and almost all the energy of the muon mass is carried by the electron. The energy spectrum of electrons from muonic atoms has a peak at the Michel edge (E_e = 52.8 MeV) with a long tail to the muon mass (m_μ = 105.7 MeV/c^2) decreasing proportionally to $(E_e\text{-}m_\mu)^{-5}$ near the end point. The mu-e conversion electron is expected to have the energy of the muon mass minus the binding energy of the muon in the muonic atom (105 MeV in the case of aluminum). Thus, the signal of the mu-e conversion process will be identified with an electron-energy peak around 105 MeV with a proper timing after the formation of the muonic atom. The background events in the mu-e conversion experiment mainly originate from pions produced at the prompt timing when the proton beam hits the pion/muon production target. A pion can be captured by a nucleus, and this process is followed by gamma emission. The gamma ray would be a source of an energetic electron through an electron-positron pair production that could be wrongly identified as a mu-e conversion signal electron. Thus, the proton beam must be pulsed with a suitable time structure, i.e., on the order of 1 μs, for the mu-e conversion measurement and should not have any particle in between consecutive pluses. This factor is called an extinction factor, defined as the ratio of the number of protons within a pulse to the number of protons outside a pulse.

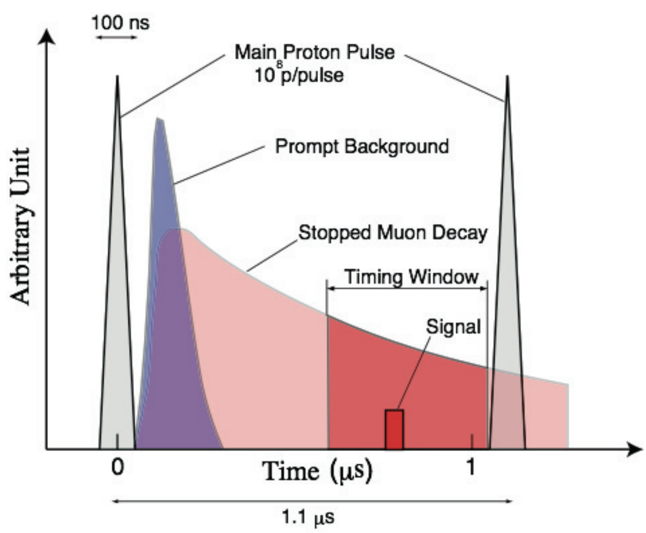

Figure 2: Time distribution of primary proton pulses, prompt background, and stopped muon decays. The timing window for data acquisition is opened 700 ns after the proton pulse arrives at the target.

Figure 2 illustrates the time distribution of primary proton pulses, prompt background, and stopped muon decays. The COMET experiment opens a time window for data acquisition 700 ns after the primary proton hits the production target in order to minimize the contribution of the prompt background. The primary proton pulse structure is realized at J-PARC by filling protons in every other acceleration bucket. The acceleration RF frequency of the J-PARC MR is 1.7 MHz, and thus, the bucket-to-bucket time width is 0.59 μs. Therefore, filling protons in every other acceleration bucket affords a suitable time structure for the mu-e conversion search experiment of 1.18 μs. Figure 3 shows an overview of the COMET apparatus. The primary proton beam hits the pion production target surrounded by a superconducting magnet to maximize the pion collection efficiency. The collected pions decay to muons during transportation to a muon transport solenoid. The muon transport solenoid magnet has a curved structure that enables us to select the muon charge and momentum with a wide momentum acceptance. This is because the center of the muon helix drifts upward or downward depending on its charge, and the drift amplitude depends on its momentum. In reality, a compensation field is applied to keep the helix of muons with required momentum at the center of the solenoid, and collimators are located at the end of the transport section to select the momentum. The muons are stopped at the muon-stopping target to form muonic atoms, and the decay electrons are measured by a spectrometer. The spectrometer consists of a curved solenoid spectrometer for momentum selection and a tracker and calorimeter located in another solenoid magnet for momentum and energy measurement.

The COMET experiment plans to achieve its target sensitivity of 10^{-16} by using an 8-GeV 50-W pulsed proton beam. The 8-GeV proton beam is suitable for the mu-e conversion experiment because the production cross-section of antiprotons, which will introduce a delayed background that can possibly be misidentified as a signal, increases rapidly above 8 GeV. The data acquisition period is planned to be 2×10^{7} s. The extinction factor of the primary proton beam must be less than 10^{-9} to reach this sensitivity. The single-event sensitivity of the experiment will be 2.6×10^{-17}, and the total amount of background is expected to be less than 0.34, resulting in the 90% confidence level upper limit of 6.0×10^{-17} in the absence of a candidate event observation.

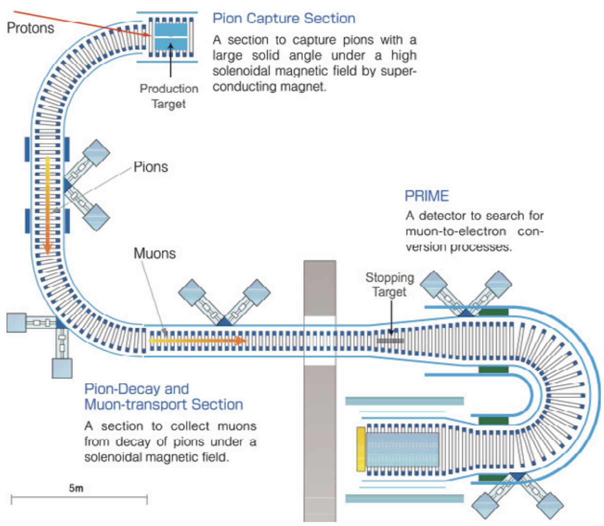

Figure 3: Overview of the COMET experiment apparatus.

Currently, the COMET collaboration is elaborating the details of the technical design of the experiment and is conducting R&D work on the primary proton beam, superconducting solenoid magnet, muon stopping target, and electron detectors. Calibration of the electron detector is also an important part of this R&D work. The collaboration plans to complete the construction of the experiment sometime around 2015. Then, an engineering run will be carried out for one year, and physics data acquisition will continue after that.

The DeeMe experiment is considered a precursor to the mu-e conversion search experiment at J-PARC. It is designed to achieve a sensitivity of 10^{-14}, which is lower by two orders of magnitude than that of the COMET experiment. However, because the DeeMe experiment can be realized in a shorter time scale thanks to its lower construction cost, it may have a chance of discovering the mu-e conversion process earlier. The experiment will use the proton beam provided at the MLF. Pions are produced by interactions between the proton beam and the production target material. Most pions decay before escaping from the target material, and the daughter particles (muons) have a chance to be trapped by the target nuclei to form muonic atoms. If such a trapped muon converts to an electron, that electron will carry the characteristic energy of the mu-e conversion process and can be identified at a delayed timing. DeeMe plans to use one of the muon beam lines from the MLF as a spectrometer to detect this electron at a delayed timing. Thus, the experiment will be simple and have reasonable acceptance. The DeeMe collaboration is currently concentrating on the beam line survey to investigate the possible background and is working on the conceptual design of a beam line kicker magnet for preventing the prompt background from entering the electron detector. Conceptual design of the electron detector is also in progress. The collaboration has submitted a proposal in 2010.

2.2. Muon g-2/EDM measurement

It is known that precise measurements of muon anomalous magnetic moment (g-2) can provide clues toward finding or restricting new physics. The anomalous electric dipole moment (EDM) of the muon is also considered a candidate probe for new physics beyond the standard model. The current most accurate measurement of the muon g-2 was carried out at BNL by the E821 collaboration, giving a deviation from the standard model prediction of $\Delta a_\mu = a_\mu^{(\mathrm{exp})} - a_\mu^{(SM)} = (295 \pm 88)\times 10^{-11}$ [9], where a_μ is defined as $a_\mu = (g-2)/2$ for $\vec{\mu} = g(e/m)\vec{s}$. Here, $\vec{\mu}$ and $\vec{s}$ are the muon magnetic dipole moment and muon spin, respectively, and e/m is the ratio of electric charge to the mass of the muon. This measurement was carried out using muons with so-called magic momentum ($p_\mu = 3.1$ GeV/c), by which the term containing the electric field disappears in the muon spin precession formula. The formula can be even simplified to $\vec{\omega} = -\,e/m\, a_\mu \vec{B}$, where $\vec{B}$ is the magnetic field to store the muons, by supposing the muon electric dipole moment (η) to be negligibly small.

The new g-2/EDM measurement at J-PARC will take a different approach to reach better measurement accuracy

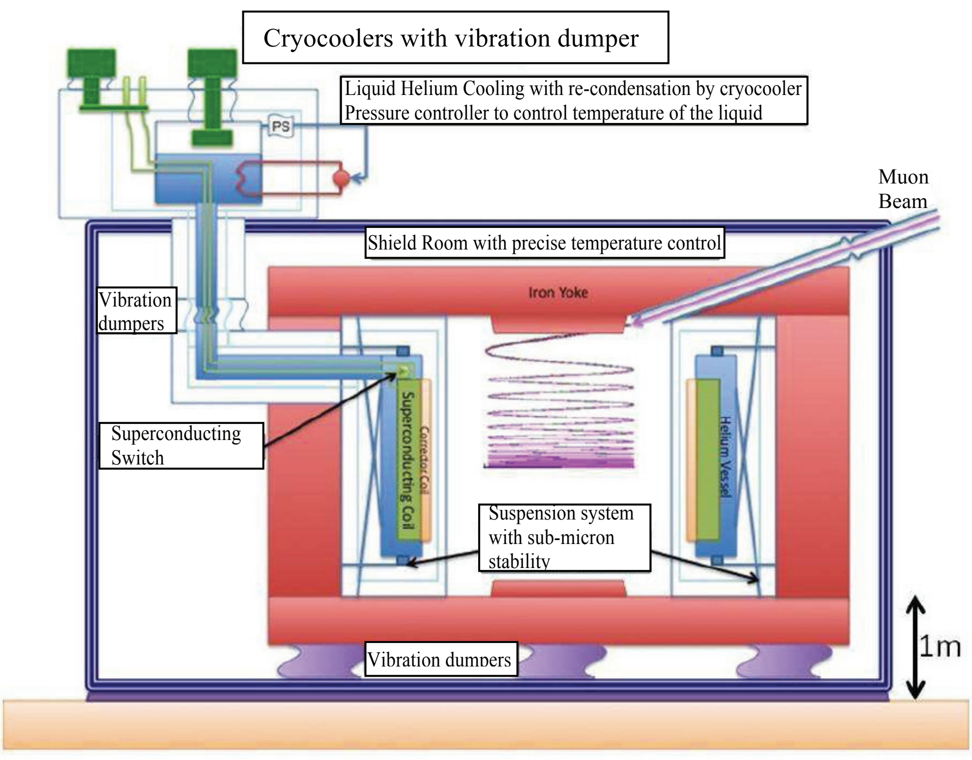

Figure 4: Schematic view of the J-PARC muon g-2/EDM experiment storage ring.

[10]. The experiment plans to use a specially prepared muon beam with a very small momentum spread. This would enable us to keep the muon beam in a storage ring without using any electric field for focusing, allowing us to conduct the experiment at any muon momentum. It should be also pointed out that this will provide a chance to measure the electric dipole moment, as can be easily understood with the spin precession formula in case of no electric field, i.e., $\vec{\omega} = -e/m\left(a_\mu \vec{B} + \eta/2\vec{\beta}\times\vec{B}\right)$.

The experiment plans to use 300 MeV/c muons with almost no transverse dispersion. The muons will be prepared by accelerating muons almost at rest (cold muons) with two linear acceleration systems dedicated to the muons. Production of such muons is one of the key technologies of this experiment. This is realized by stopping surface muons ($\mu^+ s$) provided at the MLF to form μ^+-electron atoms, muonium (Mu), in a muon stopping target and then ionizing the Mu atoms using a pulsed laser. Silicon aerogel is a candidate for the target material to maximize Mu diffusion. A small electric field is applied to extract and begin accelerating the cold muons, providing a muon beam with an extremely small transverse dispersion of 10^{-5}.

Because this experiment uses muons of 300 MeV/c, the storage ring—where muon decays are measured—can be smaller (66 cm in diameter with a 3-T field) than that of E821 (14 m in diameter with a 1.4-T field). Figure 4 shows a schematic view of the storage ring. Muons accelerated to 300 MeV/c are transferred to the ring using a spiral injection scheme and the transverse component of muon momentum is deflected into the longitudinal component. A kicker scheme is considered to stabilize the beam in a region where the uniformity of the field strength is guaranteed to be better than 1 ppm. The injected muons circulate outside the tracking system located around the center of the ring and decay to electrons and neutrinos. The decay electron distribution is measured by the tracking system, which is composed of low-mass silicon detectors. R&D of the muon source, muon linear accelerator, storage ring magnet, and electron tracking system is in progress with a view to realizing the experiment in a timely manner.

The goal of the experiment to achieve a a_μ measurement precision of 0.1 ppm using more than 100 times the number of muon decays (1.5×10^{12}) used in the previous experiment. Thorough studies to improve the muon EDM measurement sensitivity by few orders of magnitude are also in progress.

3. Summary

J-PARC has commenced operation and is increasing the beam power in a step-by–step fashion. Various kinds of secondary particles produced in proton reactions on nuclear targets have started to be used in particle and nuclear physics experiments along with materials and life science applications. Among these, the particle physics experiment using muons is the principal project. Currently, two mu-e conversion search experiments to achieve better sensitivities than the current experimental bound and one muon g-2/EDM measurement to improve the measurement accuracy are being designed to use the intense pulsed muon beam provided at J-PARC. It is strongly expected that J-PARC will be a complimentary facility to PSI in this field by taking advantage of its suitable acceleration scheme.

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